

# **ONR Graduate Traineeship Award**

Tarun K. Chandrayadula  
George Mason University  
Electrical and Computer Engineering Department  
4400 University Drive, MSN 1G5  
Fairfax, VA 22030  
phone: (703)993-1610    fax: (703)993-1601    email: [tchandra@gmu.edu](mailto:tchandra@gmu.edu)

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## **LONG-TERM GOALS**

The long term goals of this project are to investigate statistical models for signals propagating in long-range underwater channels and to design signal processing techniques to mitigate signal fluctuations due to random disturbances such as internal waves.

## **OBJECTIVES**

At long ranges, broadband receptions consist of early ray-like arrivals and a finale that is best described in terms of the low order modes. The energetic low mode signals are more strongly affected by internal wave scattering than the ray arrivals. By focusing on the low order modes, this project seeks to develop a better understanding of internal wave effects. The first objective of this project is to derive range-dependent mode statistics from experimental data obtained during the SPICE04 and LOAPEX experiments. Using these statistics, the second objective is to develop a statistical model to describe the low mode signals as a function of range. The third objective of this project is to develop new robust signal processing techniques based on the derived random channel model.

## **APPROACH**

To characterize internal wave effects on the modes, this project is using the extensive data sets of low-frequency receptions recorded as a part of the North Pacific Acoustic Laboratory (NPAL) project. Two specific experiments are particularly relevant for the current work. First, the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX) conducted in 2004 provided a unique opportunity to measure low mode receptions at a series of ranges from 50 km to 3200 km. In addition to LOAPEX, the SPICE04 experiment included transmissions from a bottom-mounted source at Kauai to a receiving array at a range of 2400 km. This project is analyzing the LOAPEX and Kauai receptions and has compared the results to Parabolic Equation (PE) simulations. The results of this analysis are being used to develop random channel models for the low order modes and subsequently to develop new signal processing techniques for these modes.

The principal investigator for this project is Mr. Tarun K. Chandrayadula, a Ph.D. student in the Electrical and Computer Engineering Department at George Mason University. Mr. Chandrayadula's thesis advisor is Professor Kathleen E. Wage.

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## WORK COMPLETED

Since the start of this project in 2006, work has focused on processing the LOAPEX and Kauai receptions and modeling internal wave effects on the low mode signals.

*Internal Wave simulations:* Internal wave simulations based on the Garrett Munk (GM) model are highly sensitive to the parameters of the spectrum. Simulations were carried out to estimate an appropriate set of parameters for use in the GM model at ranges on the order of 400 km. The estimated parameters were then used to model internal wave effects over a 400 km path.

*Simulations:* Two types of simulations have been implemented. Coupled mode simulations using the internal wave realizations were performed to calculate the amplitude and phase statistics of the components of the signal that are unaffected by scattering. PE simulations were used to model the range dependent statistics such as mean, mean envelope, temporal covariance and kurtosis of the low modes. These results have been presented at the Acoustical Society of America (ASA) meeting in November 2006 [1], the NPAL workshop in May 2007, the ASA meeting in June 2007 [2], the NPAL workshop in May 2008 and the ASA meeting in June-July 2008 [3].

*LOAPEX analysis:* The low mode signals received during LOAPEX were processed. Navigation data was missing for some parts of LOAPEX. The missing navigation data was estimated and corrections for the mooring motion and the source motion were applied to the receptions prior to mode processing. The reconstruction methods were presented at the MTS/IEEE Oceans 2008 conference in September [4].

*Kauai analysis:* The signals received during the 2004 NPAL experiment from the source deployed to the north of Kauai were processed and analyzed. Various statistics of the low order modes such as mean, variance, mean power, kurtosis, and skewness were estimated. The results of this analysis were presented at the NPAL Workshop in April 2006.

## RESULTS

Due to internal wave scattering, the mode signals at megameter ranges are spread in time and have a complicated structure [5]. As a consequence it is difficult to use these long-range mode signals in tomography. At shorter ranges, the mode signals are less scattered and might be used to obtain tomographic observables. Since the characteristics of the mode signals at short ranges are not well known, this project is using simulations and signals measured during LOAPEX to characterize these signals. The first part of this section explains the simulations that were performed to study the mode signals at short ranges. The second half of this section discusses mode processing for the LOAPEX receptions and compares the LOAPEX mode signals with the simulations.

*Statistics for the unscattered component:* Internal wave simulations were performed to model a range dependent environment over a 400 km path. The internal wave simulations were performed at a range resolution of 100 m using 150 internal wave modes. These simulation parameters were chosen as follows. According to the GM model, the internal waves have a minimum wavelength of 200 m. Using the Nyquist's sampling theorem, a range spacing of 100 m should enable us to include internal waves up to a minimum wavelength of 200 m. It was assumed that at ranges on the order of 50 km to 250 km there are approximately 80 propagating acoustic modes. Numerical simulations showed that 150

internal wave modes are adequate to model the internal wave effects on the first 80 acoustic modes.

According to the coupled mode model, the mode signal  $a_n^{(j+1)}$  at range segment  $j + 1$  due to internal waves is given by [6],

$$a_n^{(j+1)} = \sum_m C_{nm}^{(j)} a_m^{(j)}. \quad (1)$$

In Equation (1),  $C_{nm}$  is the coupling matrix. Each term in  $C_{nm}$  denotes the scattering contribution from mode  $m$  into mode  $n$ . The terms  $C_{nn}$  along the main diagonal account for that part of the mode signal that has stayed in the same mode. We refer to the part of the mode signal that has stayed in the same mode as the “unscattered component”. Reference [3] discussed the unscattered component and showed that this component has a random phase and a random amplitude that varies with range, time and frequency. In general, the unscattered component is a significant part of the mode signal at short ranges but exponentially decays with range. The unscattered component should thus be detectable at shorter ranges where the scattered energy is low. This report uses the Signal to Interference Ratio (SIR) to quantify the detectability of the unscattered component. The SIR at a given range is defined as the ratio of the mean power of the unscattered component to the mean power of the scattering contributions.

The SIR was estimated as follows. Sound Speed Profiles (SSPs) along the LOAPEX path were extracted from the World Ocean Atlas (WOA) database and averaged to obtain a background SSP. The internal wave simulations were then added to the background SSP to synthesize a range dependent environment. The modeshapes for modes 1 to 5 were calculated for each segment in a 400 km range dependent environment and used to calculate the unscattered component as a function of range. PE simulations were used to calculate the total mode signal (scattered plus unscattered) for each mode. The unscattered component for each mode was subtracted from the total mode signal to calculate the scattering contributions from all the other modes. To compute the SIR, the powers of the unscattered and scattering contributions were averaged across 100 simulations. Figure 1 shows the SIR for modes 1 to 5. Modes 1 and 4 have a high SIR for up to a range of 250 km. A narrowband energy detector with a detection threshold of 3 dB would thus be able to detect the unscattered part of modes 1 and 4 up to a range of 250 km.

*LOAPEX receptions:* As part of LOAPEX, a 75 Hz source transmitted M sequences from ranges of 50 km, 250 km, 500 km, 1600 km, 2300 km and 3200 km to a 40 element Vertical Line Array (VLA) spanning depths of 350 m to 1750 m. One of the challenges in estimating the mode signals in LOAPEX is that some of the navigation data for the LOAPEX array is missing. The array navigation data must be estimated prior to mode processing. Another challenge in mode processing for LOAPEX is the problem of environmental mismatch due to imperfect knowledge of modeshapes at the array. The first part of this section describes the estimation of the missing navigation data and the second part discusses estimating the appropriate modeshapes from environmental measurements.

*Array navigation data estimation:* The results in this section were published in reference [4]. The navigation data is missing for the upper half of the VLA at LOAPEX stations T50 and T250. A least squares filter approach based on Empirical Orthogonal Functions (EOFs) was used to estimate the missing navigation data. The EOFs for the navigation data are defined as the eigenvectors of the correlation matrix of the navigation data. The navigation data recorded at times before and after LOAPEX were used to estimate an EOF basis for the navigation data. Figure 3 shows a plot of the first

3 EOFs of the navigation data and a plot of the cumulative energy as a function of the eigenvector number. The cumulative energy plot shows that these 3 EOFs make up for more than 99.99 % of the energy in the navigation data. The missing navigation data was projected on to EOFs to estimate the navigation data for the whole array. Error statistics calculated for the EOF based estimator show that the EOF estimates have a mean error of approximately 1.5 m, which would cause a timing error in the order of approximately 1 ms. The estimation errors also caused a mean tilt of approximately  $0.13^\circ$  (measured across the 1400 m aperture of the array), which would result in a loss of approximately 0.25 dB spatial gain for modes 1 to 40. Based on these results, the EOF method can recover the missing navigation data with sufficient accuracy that there is only a minor loss in the spatial gain of the mode filter.

During some parts of LOAPEX, the navigation data is missing for both halves of the array. In one instance, navigation data is missing for half a day and at another time the navigation data is missing for 1.5 days. A model consisting of two tidal harmonics with periods of 12 hours and 24 hours was fit to the EOF coefficients around the time of the missing data. The tidal amplitudes of the two harmonics were used to extrapolate the EOF coefficients during the time of the missing data. The extrapolated coefficients were then projected on to the EOFs to estimate the missing navigation data for the entire array. A simulation was carried out to estimate the effect of the tidal estimation procedure on mode processing. The mooring data recorded over a half a day time period was used to simulate effect of array motion on mode 1 using an adiabatic model. The top left plot in Figure 4 shows the mode 1 signal perturbed due to array motion and the top right plot shows the signal compensated with the estimated navigation data. The figure shows that the estimated navigation data eliminates most of the array motion. The bottom plot in Figure 4 shows the mean envelope of mode 1 that has no motion compensation and also the mode 1 signal that has been compensated by using the mooring motion estimated from the tidal model. The plots for the mean envelope show that mode processing with the mooring data reconstructed from the tides offers almost the same averaging gain as that of using the true mooring data. Note that the averaging gain is much higher than the averaging gain with no compensation for mooring motion. The tidal reconstruction method was also used to estimate missing array navigation data for a 1.5 day period. The performance of the tidal reconstruction for this larger period had a much higher estimation error. The tidal estimation method presented here is thus not suitable for estimating the navigation data for a 1.5 day time period.

*Modeshape estimation:* Mode processing requires an accurate estimate of the modeshapes. The modeshapes depend on the SSP, which varies significantly across time. Mismatch in modeshapes causes loss in array gain and additional cross mode coupling. During LOAPEX, continuous temperature and pressure measurements were made by Seabird temperature recorders and microcats (that measured both temperature and pressure) clamped to the VLA cable. These environmental measurements provided a means to estimate the SSP at a time close to the transmissions. Thus the modeshapes for processing the T50 and T250 receptions were extracted from the environmental measurements made at a time close to the start of T50 transmissions. Figure 5 shows the results of mode processing for mode 1 with the modeshapes extracted from the Seabird sensors and the modeshapes from the WOA profile. The WOA profile mode 1 signal has a few minor arrivals occurring before the main arrival. These can be attributed to cross mode coupling induced by modeshape mismatch. The difference between the mode signal processed using the WOA profile and the Seabird profile illustrates that mode processing is extremely sensitive to environmental mismatch.

*Simulations vs LOAPEX mode signals:* Earlier work showed that internal waves cause random phase

perturbations but in a manner that the unscattered component stays together as one coherent arrival. The SIR plot showed that the unscattered component makes up for most of the mode signal at ranges in the order of 250 km. Thus an appropriate model for the mode signal at short ranges would be a single arrival that wanders in time. Figure 5 shows the mode 1 signal at station T50 received during LOAPEX. Mode 1 at station T50 has only a minor amount of scattering and is dominated by a single arrival. This agrees with the predictions based on the simulations.

## IMPACT/APPLICATIONS

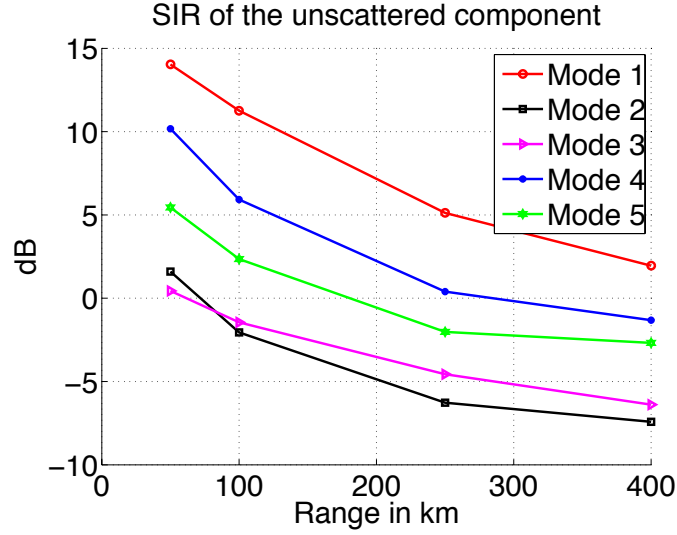
This research has both scientific and operational applications. For applications such as tomography, it is important to quantify the effects of internal waves on travel times and other parameters that might be used in an inversion. Similarly, for source detection and localization problems, it is important to understand signal fluctuations in order to assess their impact on performance. For both applications, having a statistical model of propagation through internal waves is extremely important. This project is developing a model for the unscattered component of mode signals, as well as signal processing algorithms for detecting and estimating this component. Tracking the unscattered component will facilitate the use of low mode signals in tomographic inversions. Since the low modes are only excited by submerged sources, detecting this component enhances the ability of sonar systems to discriminate between surface and submerged sources. The algorithms for mooring motion estimation presented in this report should have applications in array design and future experiment plans.

## RELATED PROJECTS

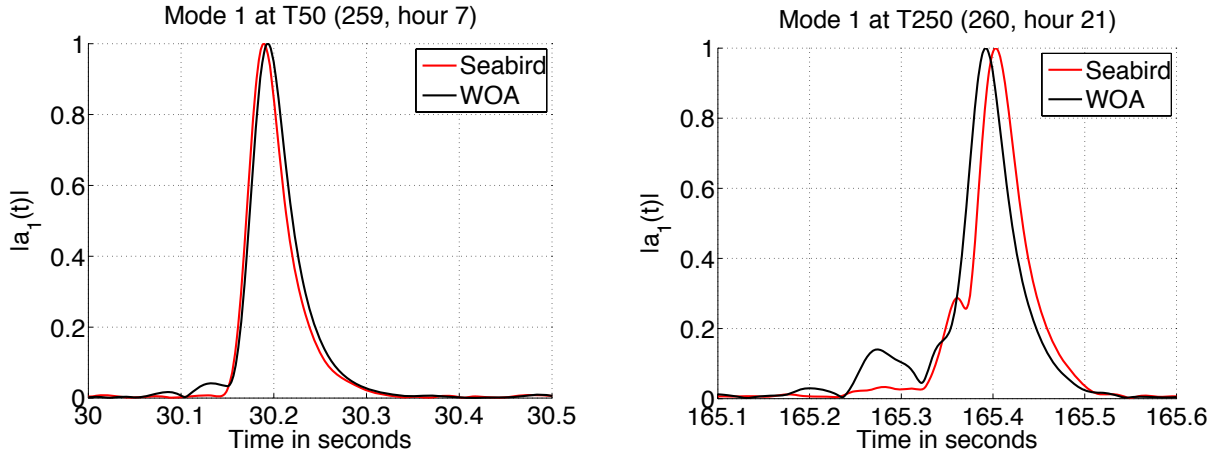
This work is closely related to ONR award N-00014-05-1-0639, which is the grant funding Mr. Chandrayadula's advisor Prof. Kathleen E. Wage and the North Pacific Acoustic Laboratory project, directed by principal investigators Peter Worcester (Scripps) and James Mercer (APL - UW). Many other ONR-sponsored researchers work on projects related to NPAL and participate in the NPAL workshops.

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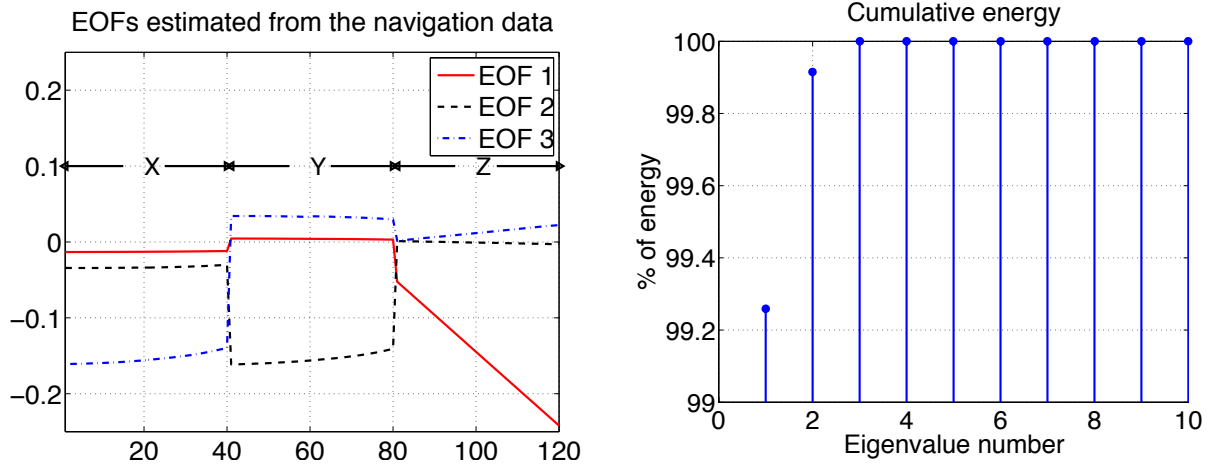
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**Figure 1:** *SIR of the unscattered component of modes 1 to 5 obtained via narrowband simulations at 75 Hz. The modes were excited at amplitudes proportional to the mode amplitudes at the LOAPEX source depth of 800 m. Modes 1 and 4 were strongly excited. A narrowband energy detector with a detection threshold of 3 dB would be able to detect modes 1 and 4 up to 250 km.*



**Figure 2:** *Mode 1 at T50 processed using the Seabird sound speed profile and the WOA profile. Note that both the mode signals were normalized to have a maximum amplitude of 1. The mode signal corresponding to the WOA profile has some early arrivals that can be attributed to cross mode coupling induced by mismatch.*



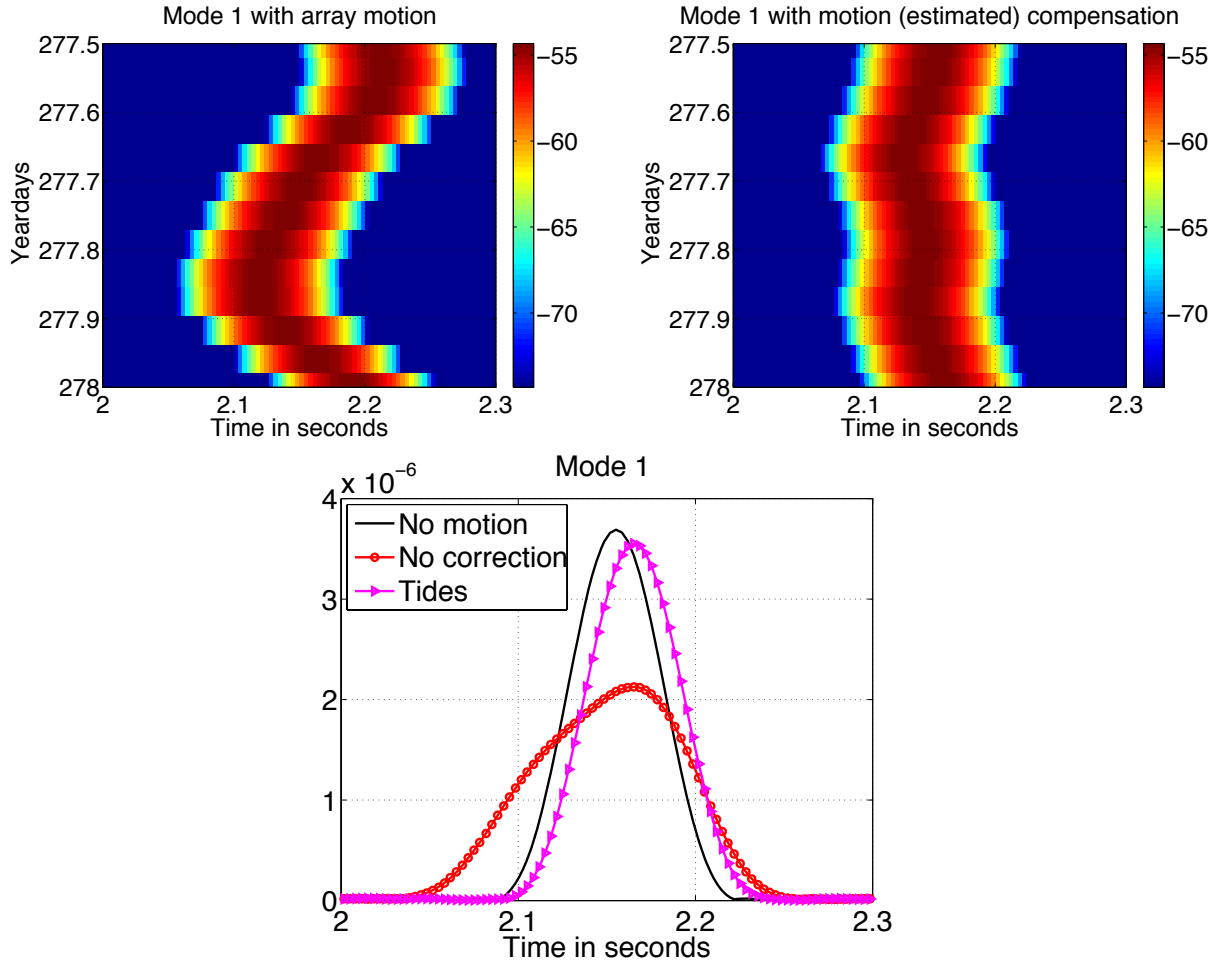
**Figure 3: EOF analysis of the navigation data.** The EOFs were estimated from the navigation data recorded during yeardays 160 to 240. Note that the displacement of the array in the X,Y and Z directions are stored in a single vector for the EOF analysis. The left plot shows the first 3 EOFs derived from the navigation data. These 3 EOFs roughly describe the shape of the array in the X, Y and Z directions and account for 99.99% of the energy in the navigation signal, as indicated in the right plot.

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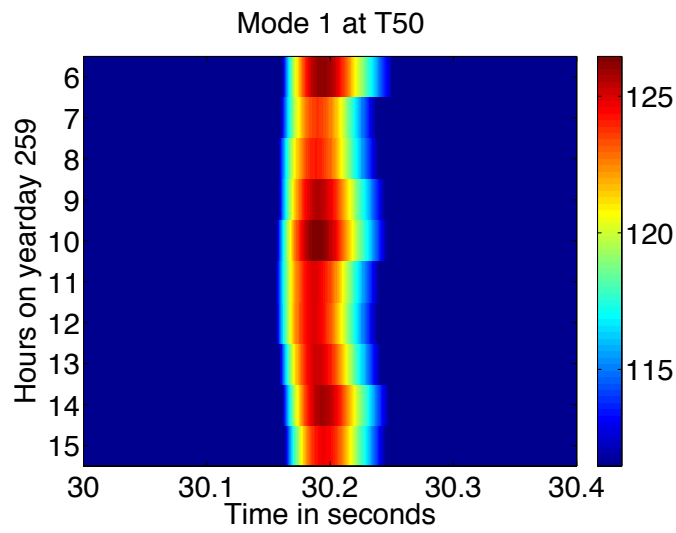
## PUBLICATIONS

Tarun K. Chandrayadula and Kathleen E. Wage, "Interpolation methods for vertical linear array element localization" in *Proceedings of the MTS/IEEE Oceans 2008 conference*, Quebec, Canada, September 2008. [In Press]





**Figure 4:** The performance of the tidal reconstruction method for half a day. The left subplot shows how the mode 1 signal would be perturbed due to array motion. The right subplot shows the mode signal compensated using the mooring motion estimated from the tidal model. The model uses 2 harmonics (12 hours and 24 hours). The bottom plot compares the average envelope of mode 1 signal for the two cases plotted above. The bottom plot also shows the average of envelope of mode 1 that has been compensated for by using the exact navigation data that was recorded. The estimation method for the navigation data does a good job in offering a much higher averaging gain than is available with no motion compensation.



***Figure 5: Mode 1 signal received at station T50 during LOAPEX. Mode processing was implemented using modeshapes extracted from the environmental measurements made along the array. The plot demonstrates that at a range of 50 km, the first mode is dominated by a single arrival.***